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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2003**	2. REPORT TYPE	3. DATES COVERED **00-00-2003 to 00-00-2003**
4. TITLE AND SUBTITLE **Modeling of Collision Avoidance Protocols in Single-Channel Multihop Wireless Networks**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of California at Santa Cruz,Department of Computer Engineering,Santa Cruz,CA,95064**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**		**30**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Modeling of Collision Avoidance Protocols in Single-Channel Multihop Wireless Networks *

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Abstract

Although there has been considerable work on the performance evaluation of collision avoidance schemes, most analytical work is confined to single-hop ad hoc networks or networks with very few hidden terminals. We present the first analytical model to derive the saturation throughput of collision avoidance protocols in multi-hop ad hoc networks with nodes randomly placed according to a two-dimensional Poisson distribution. We show that the sender-initiated collision-avoidance scheme achieves much higher throughput than the ideal carrier sense multiple access scheme with a separate channel for acknowledgments. More importantly, we show that the collision-avoidance scheme can accommodate much fewer competing nodes within a region in a network infested with hidden terminals than in a fully-connected network, if reasonable throughput is to be maintained. Simulations of the IEEE 802.11 MAC protocol and one of its variants validate the predictions made in the analysis. It is also shown that the IEEE 802.11 MAC protocol cannot ensure collision-free transmission of data packets and thus throughput can degrade well below what is predicted by the analysis of a correct collision avoidance protocol. Based on these results, a number of improvements are proposed for the IEEE 802.11 MAC protocol.

1 Introduction

An ad hoc network is a dynamic network formed on demand by a group of nodes without the aid of any pre-existing network infrastructure. An efficient and effective medium access control (MAC) protocol with which such nodes can share a common broadcast channel is essential in an ad hoc network.

Because of the "hidden terminal" problem, the performance of simple MAC protocols like the carrier sense multiple access (CSMA) protocol degrades to that of the ALOHA protocol in ad hoc networks [1]. Thus, many collision-avoidance protocols have been proposed in the recent past to combat the hidden terminal problem. The most popular collision avoidance scheme today consists of a sender-initiated four-way handshake in which the transmission of a data packet and its acknowledgment is preceded by short request-to-send (RTS) and clear-to-send (CTS) packets between a pair of sending and receiving nodes.[1] Other nodes that overhear RTS or CTS packets defer their access to the channel to avoid collisions. The specific sender-initiated collision avoidance protocols differ in the lengths of control packets, whether packet sensing or carrier sensing is used, and the choice of backoff schemes. Among all the proposed collision-avoidance protocols, the IEEE 802.11 distributed foundation wireless medium access control (DFWMAC) protocol [3] has become a de facto standard in performance studies of routing protocols for ad hoc networks, even though it was originally intended for wireless LANs with no or very few hidden terminals. The DFWMAC protocol is based on a four-way handshake with non-persistent carrier sensing.

Since the inception of the IEEE 802.11 working group, there has been considerable work on the performance evaluation of IEEE 802.11 in wireless LANs and possible ways to enhance its performance [4–11]. Some of them are simulation based, others also use analytical models. However, the analytical models of collision-avoidance protocols

*This work was supported in part by the Defense Advanced Research Projects Agency (DARPA) under Grant No. DAAD19-01-C-0026 and by the US Air Force/OSR under Grant No. F49620-00-1-0330.

[1] This is in contrast to receiver-initiated MAC schemes (e.g. [2]) in which the collision avoidance handshake is started by receivers.

so far are largely confined to single-hop networks [9–11] or cases when the number of hidden terminals is very small [4, 5]. They cannot capture a salient feature of ad hoc networks, i.e., potential interference from hidden nodes always exists. Hence, we are interested in investigating the performance of the sender-initiated collision avoidance scheme based on a four-way handshake in a general framework that is more applicable to ad hoc networks. Our work is different from the work done by Gupta and Kumar [12] in that the authors give very general results about the capacity of wireless networks from an information-theory centric view, while our analysis and simulation experiments show how the typical collision-avoidance MAC protocols can perform in multi-hop ad hoc networks.

In Section 2, we present the analysis of the sender-initiated collision-avoidance scheme based on a four-way handshake and non-persistent carrier sensing, which can be also called the RTS/CTS-based scheme for the sake of simplicity. To our knowledge, this is the first analytical modeling of collision avoidance in multi-hop networks. We first adopt a simple model in which nodes are randomly placed on a plane according to two-dimensional Poisson distribution with density λ. Varying λ has the effect of changing the congestion level within a region as well as the number of hidden terminals. In this model, it is also assumed that each node is ready to transmit independently in each time slot with probability p, where p is a protocol-dependent parameter. This model was first used by Takagi and Kleinrock [13] to derive the optimum transmission range of a node in a multi-hop wireless network, and was used subsequently by Wu and Varshney [14] to derive the throughputs of non-persistent CSMA and some variants of busy tone multiple access (BTMA) protocols [1]. Then we assume that both carrier sensing and collision avoidance work perfectly, that is, that nodes can accurately sense the channel busy or idle, and that the RTS/CTS scheme can avoid the transmission of data packets that collide with other packets at the receivers. The latter assumption can be called *perfect collision avoidance* and has been shown to be doable in the floor acquisition multiple access (FAMA) protocol [15]. Later we extend this model to take into account the possibility of data packets colliding with other transmissions, so that the model is also applicable to other MAC protocols, such as the popular IEEE 802.11 protocol, in which perfect collision avoidance is not strictly enforced.

In Section 3, we present numerical results from our analysis. We compare the performance of the sender-initiated collision avoidance scheme against the idealized non-persistent CSMA protocol in which a secondary channel is assumed to send acknowledgments in zero time and without collisions [1, 14], as the latter is the only protocol whose analysis for multi-hop ad hoc networks is available for comparison to date. It is shown that the RTS/CTS scheme can achieve far better throughput than the CSMA protocol, even when the overhead due to RTS/CTS exchange is high. The results illustrate the importance of enforcing collision avoidance in the RTS/CTS handshake. However, the analytical results also indicate that the aggregate throughput of sender-initiated collision avoidance drops faster than that in a fully-connected network when the number of competing nodes within a region increases. This contrasts with conclusions drawn from the analysis of collision avoidance in fully-connected networks or networks with limited hidden terminals [15]. Our results show that hidden terminals degrade the performance of collision avoidance protocols beyond the basic effect of having a longer vulnerability period for RTSs. Hence, it follows that collision avoidance becomes more and more ineffective for a relatively crowded region with hidden terminals.

To validate the findings drawn from this analysis, in Section 4 we present simulations of the popular IEEE 802.11 MAC protocol. The simulation results clearly show that the IEEE 802.11 MAC protocol cannot ensure collision-free transmission of data packets, and that almost half of the data packets transmitted cannot be acknowledged due to collisions, even when the number of competing nodes in a neighborhood is only eight! We also investigate a variant of the IEEE 802.11 MAC protocol in which the contention window used in deciding backoff time is fixed. This variant does not have the inherent fairness problem in the original binary exponential backoff (BEB) scheme used in the IEEE 802.11 MAC protocol, though it is not fine tuned to achieve the best performance. However, the simulation results do show that decreasing the contention window leads to more collisions of data packets, while increasing the contention window leads to more wasted time in waiting. Both approaches can limit the maximum achievable throughput significantly, which is a typical dilemma for contention-based MAC protocols, especially for those that do not provide *correct* collision avoidance scheme in less crowded multi-hop networks. The performance of the simulated IEEE 802.11 MAC protocol correlates well with what is predicted in the extended analysis, which takes into account the effect of data packet collisions and is used for the case when the number of competing nodes in a region is small. When the number of competing nodes in a region increases, the performance gap between IEEE 802.11 and the analysis decreases, which validates the statement that even a perfect collision-avoidance protocol loses its effectiveness gradually due to the random nature of the channel access and the limited information available to competing nodes.

Section 5 concludes this paper with possible ways to improve the performance of collision avoidance protocols in

ad hoc networks and highlights the usage of directional antennas, which calls for further analytical work.

2 Approximate Analysis

In this section, we derive the approximate throughput of a perfect collision avoidance protocol. In our network model, nodes are two-dimensionally Poisson distributed over a plane with density λ, i.e., the probability $p(i, S)$ of finding i nodes in an area of S is given by:

$$p(i, S) = \frac{(\lambda S)^i}{i!} e^{-\lambda S}.$$

Assume that each node has the same transmission and receiving range of R, and denote by N the average number of nodes within a circular region of radius R; therefore, we have $N = \lambda \pi R^2$.

To simplify our analysis, we assume that nodes operate in time-slotted mode. As prior results for CSMA and collision-avoidance protocols show [1], the performance of MAC protocols based on carrier sensing is much the same as the performance of their time-slotted counterparts in which the length of a time slot equals one propagation delay and the propagation delay is much smaller than the transmission time of data packets.

The length of each time slot is denoted by τ. Note that τ is not just the propagation delay, because it also includes the overhead due to the transmit-to-receive turn-around time, carrier sensing delay and processing time. In effect, τ represents the time required for all the nodes within the transmission range of a node to know the event that occurred τ seconds ago. The transmission times of RTS, CTS, data, and ACK packets are normalized with regard to τ, and are denoted by l_{rts}, l_{cts}, l_{data}, and l_{ack}, respectively. Thus, τ is also equivalent to 1 in later derivations. For the sake of simplicity, we also assume that all packet transmission times are multiples of the length of a time-slot.

We derive the protocol's throughput based on the heavy-traffic assumption, i.e., a node always has a packet in its buffer to be sent and the destination is chosen randomly from one of its neighbors. This is a fair assumption in ad hoc networks in which nodes are sending data and signaling packets continually. We also assume that a node is ready to transmit with probability p and not ready with probability $1 - p$. Here p is a protocol-specific parameter that is slot independent. At the level of individual nodes, the probability of being ready to transmit may vary from time slot to slot, depending on the current states of both the channel and the node. However, because we are interested in deriving the average performance metrics instead of instantaneous or short-term metrics, the assumption of a fixed probability p may be considered as an averaged quantity that can still reasonably approximate the factual burstiness from a long-term point of view. In fact, this assumption is necessary to make the theoretical modeling tractable and has been extensively applied before [11, 13, 14]. For example, this model was used by Takagi and Kleinrock [13] to derive the optimal transmission range of a node in a multi-hop wireless network, and was used subsequently by Wu and Varshney [14] to derive the throughput of non-persistent CSMA and some variants of busy tone multiple access (BTMA) protocols [1].

It should also be noted that, even when a node is ready to transmit, it may transmit or not in the slot, depending on the collision avoidance and resolution schemes being used, as well as the channel's current state. Thus, we are more interested in the probability that a node transmits in a time slot, which is denoted by p'. Similar to the reasoning presented for p, we also assume that p' is independent at any time slot to make the analysis tractable. Given this simplification, p' can be defined to be

$$\begin{aligned} p' &= p \cdot \text{Prob.}\{\text{Channel is sensed idle in a slot}\} \\ &\approx p \cdot \Pi_I \end{aligned}$$

where Π_I is the limiting probability that the channel is in idle state, which we derive subsequently.

We are not interested in the exact relationship between p and p', and it is enough to obtain the range of values that p' can take, because the throughput of these protocols is mostly influenced by p'. To derive the rough relationship between p and p', we set up a channel model that includes two key simplifying assumptions.

First, we model the channel as a circular region in which there are some nodes. The nodes within the region can communicate with each other while they have weak interactions with nodes outside the region. *Weak interaction* means that the decision of inner nodes to transmit, defer and back off is almost not affected by that of outer nodes and vice versa. Considering that nodes do not exchange status information explicitly (e.g., either defer due to collision

avoidance or back off due to collision resolution), this assumption is reasonable and helps to simplify the model considerably. Thus, the channel's status is only decided by the successful and failed transmissions within the region.

Second, we still consider the failed handshakes initiated by nodes within the region to outside nodes, because this has a direct effect on the channel's usability for other nodes within the region. Though the radius of the circular region R' is unknown, it falls between $R/2$ and $2R$. This follows from noting that the maximal radius of a circular region in which all nodes are guaranteed to hear one another equals $R' = R/2$, and all the direct neighbors and hidden nodes are included into the region when $R' = 2R$. Thus, we obtain $R' = \alpha R$ where $0.5 \leq \alpha \leq 2$, and α needs to be estimated.

With the above assumptions, the channel can be modeled by a four-state Markov chain illustrated in Figure 1. The significance of the states of this Markov chain is the following:

- *Idle* is the state when the channel around node x is sensed idle, and obviously its duration is τ.
- *Long* is the state when a successful four-way handshake is done. For simplicity, we assume that the channel is in effect busy for the duration of the whole handshake, thus the busy time T_{long} is

$$\begin{aligned} T_{long} &= l_{rts} + \tau + l_{cts} + \tau + l_{data} + \tau + l_{ack} + \tau \\ &= l_{rts} + l_{cts} + l_{data} + l_{ack} + 4\tau. \end{aligned}$$

- *Short1* is the state when multiple nodes around the channel transmit RTS packets during the same time slot and their transmissions collide. The busy time of the channel T_{short1} is therefore

$$T_{short1} = l_{rts} + \tau.$$

- *Short2* is the state when one node around the channel initiates a failed handshake with a node outside the region. Even though a CTS packet may not be sent due to the collision of the sending node's RTS packet with other packets originated from nodes outside the region or due to the deferring of the receiving node to other nodes, those nodes overhearing the RTS as well as the sending node do not know if the handshake is successfully continued, until the time required for receiving a CTS packet elapses. Therefore the channel is in effect busy, i.e., unusable for all the nodes sharing the channel, for the time stated below:

$$\begin{aligned} T_{short2} &= l_{rts} + \tau + l_{cts} + \tau \\ &= l_{rts} + l_{cts} + 2\tau. \end{aligned}$$

Now we proceed to calculate the transition probabilities of the Markov chain.

In most collision avoidance schemes with non-persistent carrier sensing, no node is allowed to transmit immediately after the channel becomes idle, thus the transition probabilities from *long* to *idle*, from *short1* to *idle* and from *short2* to *idle* are all 1.

According to the Poisson distribution of the nodes, the probability of having i nodes within the receiving range R of x is $e^{-N}N^i/i!$, where $N = \lambda\pi R^2$. Therefore, the mean number of nodes that belong to the shared channel is $M = \lambda\pi {R'}^2 = \alpha^2 N$. Assuming that each node transmits independently, the probability that none of them transmits is $(1-p')^i$, where $(1-p')$ is the probability that a node does not transmit in a time slot. Because the transition probability P_{ii} from *idle* to *idle* is the probability that none of the neighboring nodes of x transmits in this slot, P_{ii} is given by

$$\begin{aligned} P_{ii} &= \sum_{i=0}^{\infty}(1-p')^i \frac{M^i}{i!}e^{-M} \\ &= \sum_{i=0}^{\infty}\frac{[(1-p')M]^i}{i!}e^{-(1-p')M} \cdot e^{-p'M} \\ &= e^{-p'M}. \end{aligned}$$

We average the probabilities over the number of interfering nodes in a region because of two reasons. First, it is much more tractable than the approach that conditions on the number of nodes, calculates the desired quantities, and then uses the Poisson distribution to obtain the average. Second, in our simulation experiments, we fix the number

of competing nodes in a region (which is N) and then vary the location of the nodes to approximate the Poisson distribution, which is configurationally closer to our analytical model; the alternative would be to generate 2, 3, 4, ... nodes within one region, get the throughput for the individual configuration and then calculate the average, which is not practical.

Next we need to calculate the transition probability P_{il} from *idle* to *long*. If there are i nodes around node x, for such a transition to happen, one and only one node should be able to complete one successful four-way handshake while other nodes do not transmit. Let p_s denote the probability that a node begins a successful four-way handshake at each slot, we can then calculate P_{il} as follows:

$$\begin{aligned}P_{il} &= \sum_{i=1}^{\infty} i p_s (1-p')^{i-1} \frac{M^i}{i!} e^{-M} \\ &= \sum_{i=1}^{\infty} p_s (1-p')^{i-1} \frac{M^{i-1}}{(i-1)!} M e^{-M} \\ &= p_s M \sum_{i=0}^{\infty} \frac{[M(1-p')]^i}{i!} e^{-M(1-p'+p')} \\ &= p_s M e^{-p'M}.\end{aligned}$$

To obtain the above result, we use the fact that the distribution of the number of nodes within R' does not depend on the existence of node x, because of the memoryless property of the Poisson distribution. Up to this point, p_s is still an unknown quantity that we derive subsequently.

The transition probability from *idle* to *short1* is the probability that more than one node transmit RTS packets in the same slot; therefore, P_{is1} can be calculated as follows:

$$\begin{aligned}P_{is1} &= \sum_{i=2}^{\infty} [1-(1-p')^i - ip'(1-p')^{i-1}] \frac{M^i}{i!} e^{-M} \\ &= 1-(1+Mp')e^{-p'M}.\end{aligned}$$

Having calculated P_{ii}, P_{il} and P_{is1}, we can calculate P_{is2}, the transition probability from *idle* to *short2*

$$\begin{aligned}P_{is2} &= 1 - P_{ii} - P_{il} - P_{is1} \\ &= 1 - e^{-p'M} - p_s M e^{-p'M} - (1-(1+Mp')e^{-p'M}) \\ &= (p' - p_s) M e^{-p'M}.\end{aligned}$$

Let π_i, π_l, π_{s1} and π_{s2} denote the steady-state probabilities of states *idle*, *long*, *short1* and *short2*, respectively. From Figure 1, we have

$$\begin{aligned}\pi_i P_{ii} + \pi_l + \pi_{s1} + \pi_{s2} &= \pi_i \\ \pi_i P_{ii} + 1 - \pi_i &= \pi_i \\ \pi_i &= \frac{1}{2 - P_{ii}} = \frac{1}{2 - e^{-p'M}}.\end{aligned}$$

The limiting probability Π_I, i.e., the long run probability that the channel around node x is found idle, can be obtained by:

$$\Pi_I = \frac{\pi_i T_{idle}}{\pi_i T_{idle} + \pi_l T_{long} + \pi_{s1} T_{short1} + \pi_{s2} T_{short2}}.$$

Noting that $\pi_i P_{il} = \pi_l, \pi_i P_{is1} = \pi_{s1}$ and $\pi_i P_{is2} = \pi_{s2}$, we obtain

$$\begin{aligned}\Pi_I &= \frac{\pi_i T_{idle}}{\pi_i T_{idle} + \pi_i P_{il} T_{long} + \pi_i P_{is1} T_{short1} + \pi_i P_{is2} T_{short2}} \\ &= \frac{T_{idle}}{T_{idle} + P_{il} T_{long} + P_{is1} T_{short1} + P_{is2} T_{short2}}.\end{aligned}$$

The relationship between p' and p is then:

$$\begin{aligned} p' &= \frac{pT_{idle}}{T_{idle} + P_{il}T_{long} + P_{is1}T_{short1} + P_{is2}T_{short2}} \\ &= \frac{pT_{idle}}{T_{idle} + p_s M e^{-p'M} T_{long} + (1-(1+p'M)e^{-p'M})T_{short1} + (p'-p_s)Me^{-p'M}T_{short2}} \\ &= \frac{p\tau}{\tau + p_s M e^{-p'M}(l_{rts} + l_{cts} + l_{data} + l_{ack} + 4\tau) + (1-(1+p'M)e^{-p'M})(l_{rts}+\tau) + \cdots} \\ &\qquad \overline{\cdots + (p'-p_s)Me^{-p'M}(l_{rts} + l_{cts} + 2\tau)} \end{aligned} \tag{1}$$

In the above equation, the probability that a node x starts successfully a four-way handshake in a time slot, p_s, is yet to be determined.

The states of a node x can be modeled by a three-state Markov chain, which is shown in Figure 2. In Figure 2, *wait* is the state when the node defers for other nodes or backs off, *succeed* is the state when the node can complete a successful four-way handshake with other nodes, and *fail* is the state when the node initiates an unsuccessful handshake. For simplicity, we regard *succeed* and *fail* as the states when two different kinds of *virtual* packets are transmitted and their lengths are:

$$\begin{aligned} T_{succeed} &= T_{long} \\ &= l_{rts} + l_{cts} + l_{data} + l_{ack} + 4\tau \\ T_{fail} &= T_{short2} \\ &= l_{rts} + l_{cts} + 2\tau. \end{aligned}$$

Obviously, the duration of a node in *wait* state T_{wait} is τ.

Because by assumption collision avoidance is enforced at each node, no node is allowed to transmit data packets continuously; therefore, the transition probabilities from *succeed* to *wait* and from *fail* to *wait* are both one.

To derive the transition probability P_{ws} from *wait* to *succeed*, we need to calculate the probability $P_{ws}(r)$ that node x successfully initiates a four-way handshake with node y at a given time slot when they are at a distance r apart. Before calculating $P_{ws}(r)$, we define $B(r)$ to be the area that is in the hearing region of node y but outside the hearing region of node x, i.e., the interfering region "hidden" from node x as the shaded area shown in Figure 3. $B(r)$ has been shown in [13] to be:

$$B(r) = \pi R^2 - 2R^2 q\left(\frac{r}{2R}\right) \tag{2}$$

where $q(t) = \arccos(t) - t\sqrt{1-t^2}$.

Then $P_{ws}(r)$ can be calculated as:

$$P_{ws}(r) = P_1 \cdot P_2 \cdot P_3 \cdot P_4(r)$$

where

$$\begin{aligned} P_1 &= \text{Prob.}\{x \text{ transmits in a slot}\}, \\ P_2 &= \text{Prob.}\{y \text{ does not transmit in the time slot}\}, \\ P_3 &= \text{Prob.}\{\text{none of the terminals within } R \text{ of } x \text{ transmits in the same slot}\}, \\ P_4(r) &= \text{Prob.}\{\text{none of the terminals in } B(r) \text{ transmits for } (2l_{rts}+1) \text{ slots} \mid r\}. \end{aligned}$$

The reason for the last term is that the vulnerable period for an RTS is only $2l_{rts} + 1$, and once the RTS is received successfully by the receiving node (which can then start sending the CTS), the probability of further collisions is assumed to be negligibly small.

Obviously, $P_1 = p'$ and $P_2 = (1 - p')$. On the other hand, P_3 can be obtained by

$$\begin{aligned} P_3 &= \sum_{i=0}^{\infty} (1-p')^i \frac{(\lambda \pi R^2)^i}{i!} e^{-\lambda \pi R^2} \\ &= \sum_{i=0}^{\infty} (1-p')^i \frac{N^i}{i!} e^{-N} \\ &= e^{-p'N}. \end{aligned}$$

Similarly, the probability that none of the terminals in $B(r)$ transmits in a time slot is given by

$$\begin{aligned} p_4(r) &= \sum_{i=0}^{\infty} (1-p')^i \frac{(\lambda B(r))^i}{i!} e^{-\lambda B(r)} \\ &= e^{-p' \lambda B(r)}. \end{aligned}$$

Hence, $P_4(r)$ can be expressed as

$$\begin{aligned} P_4(r) &= (p_4(r))^{2l_{rts}+1} \\ &= e^{-p' \lambda B(r)(2l_{rts}+1)}. \end{aligned}$$

Given that each sending node chooses any one of its neighbors with equal probability and that the average number of nodes within a region of radius r is proportional to r^2, the probability density function of the distance r between node x and y is

$$f(r) = 2r, \quad 0 < r < 1.$$

where we have normalized r with regard to R by setting $R = 1$.

Now we can calculate P_{ws} as follows:

$$\begin{aligned} P_{ws} &= \int_0^1 2r P_{ws}(r) dr \\ &= 2p'(1-p')e^{-p'N} \int_0^1 r e^{-p' \lambda B(r)(2l_{rts}+1)} dr \\ &= 2p'(1-p')e^{-p'N} \int_0^1 r e^{-p' N[1-2q(r/2)/\pi](2l_{rts}+1)} dr. \end{aligned} \tag{3}$$

From the Markov chain shown in Figure 2, the transition probability P_{ww} that node x continues to stay in *wait* state in a slot is just $(1-p')e^{-p'N}$, i.e., node x does not initiate any transmission and there is no node around it initiating a transmission. Let π_s, π_w and π_f denote the steady-state probability of state *succeed*, *wait* and *fail*, respectively. From Figure 2, we have

$$\begin{aligned} \pi_w P_{ww} + \pi_s + \pi_f &= \pi_w \\ \pi_w P_{ww} + 1 - \pi_w &= \pi_w \\ \pi_w &= \frac{1}{2 - P_{ww}} = \frac{1}{2 - (1-p')e^{-p'N}}. \end{aligned}$$

Therefore, the steady-state probability of state *succeed*, π_s, can be calculated as:

$$\pi_s = \pi_w P_{ws} = \frac{P_{ws}}{2 - (1-p')e^{-p'N}} = p_s. \tag{4}$$

Equation (4) points out the fact that π_s is just the previous unknown quantity p_s in Equation (1). Combining Equations (1), (3) and (4) together, we get a complex relationship between p and p'. However, given p, p' can be computed easily with numerical methods.

Accordingly, the throughput Th is:

$$
\begin{aligned}
Th &= \frac{\pi_s \cdot l_{data}}{\pi_w T_{wait} + \pi_s T_{success} + \pi_f T_{fail}} \\
&= \frac{l_{data}\pi_s}{\tau\pi_w + (l_{rts} + l_{cts} + 2\tau)(1 - \pi_w - \pi_s) + (l_{rts} + l_{cts} + l_{data} + l_{ack} + 4\tau)\pi_s} \\
&= \frac{l_{data}P_{ws}}{\tau + (l_{rts} + l_{cts} + 2\tau)(1 - P_{ws} - (1-p')e^{-p'N}) + (l_{rts} + l_{cts} + l_{data} + l_{ack} + 4\tau)P_{ws}}. \qquad (5)
\end{aligned}
$$

From the formula used to calculate throughput, we can see that π_s and π_w, from which throughput is derived, are largely dependent on p' and not on p, which is the basis for our simplification of the modeling of the channel presented earlier.

To apply our analysis to MAC protocols in which perfect collision avoidance is not enforced, e.g., the IEEE 802.11 MAC protocol, we propose a simple though not rigorous extension of the analysis. We can add another state to the Markov chain for the node model (ref. Figure 2) whose duration is $l_{rts} + l_{cts} + l_{data} + 3\tau$. This is a *pseudo-succeed* state in which an RTS-CTS-data handshake takes place without acknowledgment coming back due to collisions, i.e., it is a state derived from the *succeed* state of the perfect collision avoidance protocol. We use an "imperfectness factor" β to model the deviatory behavior of the protocol, given that different MAC protocols may have different values of β. The transition probability from *wait* to the *pseudo-succeed* state is then βP_{ws}, and the transition probability from *wait* to *succeed* is $(1-\beta)P_{ws}$. Hence, the modified formula for throughput is simply:

$$
\begin{aligned}
Th &= (1-\beta)l_{data}\pi_s[\tau\pi_w + (l_{rts} + l_{cts} + l_{data} + l_{ack} + 4\tau)(1-\beta)\pi_s \\
&\quad + (l_{rts} + l_{cts} + 2\tau)(1 - \pi_w - \pi_s) + (l_{rts} + l_{cts} + l_{data} + 3\tau)\beta\pi_s]^{-1} \\
&= (1-\beta)l_{data}P_{ws}[\tau + (l_{rts} + l_{cts} + l_{data} + l_{ack} + 4\tau)(1-\beta)P_{ws} \\
&\quad + (l_{rts} + l_{cts} + 2\tau)(1 - P_{ws} - (1-p')e^{-p'N}) + (l_{rts} + l_{cts} + l_{data} + 3\tau)\beta P_{ws}]^{-1}. \qquad (6)
\end{aligned}
$$

When the deviatory factor β equals zero, Equation (6) is reduced to Equation (5).

3 Numerical Results

In this section, we compare the throughput of the RTS/CTS scheme with a non-persistent CSMA protocol in which there is a separate channel over which acknowledgments are sent in zero time and without collisions. The performance of the latter protocol in multi-hop networks has been analyzed by Wu and Varshney [14] and we should note that, in practice, the performance of the CSMA protocol would be worse as both data packets and acknowledgments are transmitted in the same channel.

We present results when either relatively large data packets or relatively small data packets are sent. Let τ denote the duration of one time slot. RTS, CTS and ACK packets last 5τ. As to the size of data packets, we consider two cases. One case corresponds to a data packet that is much larger than the aggregate size of RTS, CTS and ACK packets. The other case corresponds to a data packet being only slightly larger than the aggregate size of RTS, CTS and ACK packets. In the latter case, which models networks in which radios have long turn-around times and data packets are short, it is doubtful whether a collision avoidance scheme should be employed at all, because it represents excessive overhead.

We first calculate throughput with different values of α, which we define as the ratio between the circular region including nodes affected by an RTS/CTS handshake and the largest possible circular region in which nodes are guaranteed to be connected with one another. We find that, though the relationship between the ready probability p and transmission-attempt probability p' under different values of α might be somewhat different, the throughput is largely unaffected by α, which is shown in Figure 4.[2] In Figure 4, N is the average number of nodes that compete against one another to access the shared channel. Thus, the burden of estimating α is relieved in our model, and we can focus on the case in which $\alpha = 1$ thereafter. However, as a side effect of not knowing the actual α that should be used, the relationship between p' and throughput may not agree with the simulations. However, for our purposes this is not a problem, because we are interested in the saturated throughput only.

[2] The curves for $N = 3$ with different values of α concentrates on the upper part of these figures while the ones for $N = 10$ on the lower part.

Figure 5 compares the throughput of collision avoidance against that of CSMA with different values of N and data packet lengths, and we can make the following observations from the above results.

When data packet is long, the throughput of CSMA is very low, even for the case in which only $N = 3$ nodes are competing for the shared channel. By comparison, the RTS/CTS scheme can achieve much higher throughput, even when the average number of competing nodes is 10. The reason is simple, the larger a data packet is, the worse the impact of hidden terminals is for that packet in CSMA, because the vulnerability period becomes twice the length of the data packet. With collision avoidance, the vulnerability period of a handshake is independent of the length of data packets, and in the worse case, equals twice the length of an RTS. When a data packet is not very long and the overhead of the collision avoidance and handshake seems to be rather high, collision avoidance can still achieve marginally better throughput than CSMA. We need to emphasize that the performance of the actual CSMA protocol would be much worse than the idealized model we have used for comparison purposes, because of the effect of acknowledgments.

Despite the advantage of collision avoidance, its throughput still degrades rapidly with the increase of N. This is also evident for low values of p' as shown in Figure 5. This is due the fact that nodes are spending much more time on collision avoidance and backoff. When N increases, p' decreases much slower to achieve optimum throughput, which already decreases. This shows that collision avoidance becomes more and more ineffective when the number of competing nodes within a region increases, even though these nodes are quite "polite" in their access to the shared channel. This is also different from a fully-connected network, in which the maximum throughput is largely indifferent to the number of nodes within a region [9].

Our results also reveal that hidden terminals degrade the performance of collision avoidance protocols beyond the basic effect of having a longer vulnerability period for RTSs. There is one dilemma here. On the one hand, it is very difficult to get all the competing nodes around one node coordinated well by probabilistic methods such as randomized backoff. Here the competing nodes refer to both one-hop and two-hop neighbors[3] of the node. In actual MAC protocols, the collisions of data packets may still occur and throughput degrades with increasing numbers of neighbors. On the other hand, even if all the competing nodes of one node defer their access for the node, the possible spatial reuse in multi-hop networks is greatly reduced and hence the maximum achievable throughput is reduced. This dilemma leads to the scalability problem of contention-based MAC protocols that occurs much earlier than people might expect, as the throughput is already quite meager when the average of competing nodes within a region (N) is only ten.

4 Simulation Results

The numerical results in the previous section show that an RTS/CTS based access scheme outperforms CSMA, even when the overhead of RTS/CTS packets is comparable to the data packets to be transmitted if perfect collision avoidance can be achieved. In this section, we investigate the performance of the popular IEEE 802.11 DFWMAC protocol, and one of its variants that uses fixed contention window, to validate the predictions made in the analysis.

We use GloMoSim 2.0 [16] as the network simulator. Direct sequence spread spectrum (DSSS) parameters are used throughout the simulations, which are shown in Table 1. The raw channel bit rate is 2Mbps. We use a uniform distribution to approximate the Poisson distribution used in our analytical model, because the latter is mainly used to facilitate our derivation of analytical results. In addition, it is simply impractical to generate 2, 3, 4, ... nodes within one region, get the throughput for the individual configuration and then calculate the average like what is required in the analytical model. In the network model used simulations, we place nodes in concentric circles or rings as illustrated in Figure 6. That is, given that a node's transmitting and receiving range is R and that there are on average N nodes within this circular region, we place N nodes in a circle of radius R, subject to a uniform distribution. Because there are on average 2^2N nodes within a circle of radius $2R$, we place $2^2N - N = 3N$ nodes outside the previous circle of radius R but inside the concentric circle of radius $2R$, i.e., the ring with radii R and $2R$, subject to the same uniform distribution. Then $3^2N - 2^2N = 5N$ nodes can be placed in an outer ring with radii $2R$ and $3R$.

Because it is impossible to generate the infinite network we assumed in our analysis in simulations, we just focus our attention on the performance of the innermost N nodes. Another reason is that it is more appropriate to investigate the performance of MAC schemes in a local neighborhood, rather than in the whole network, because totaling and

[3] Here we refer to those nodes that have at least one common neighbor with a node but are not direct neighbors of the node as the node's two-hop neighbors.

averaging performance metrics such as throughput and delay with regard to all the nodes both in the center and at the edge of a network may lead to some askew results. For example, nodes at the edge may have exceedingly high throughput due to much less contention and including them in the calculation would lead to higher than usual throughput. In our experiments, we find that nodes that are outside the concentric circles of radius $3R$ almost have no influence on the throughput of the innermost N nodes, i.e., boundary effects can be safely ignored when the circular network's radius is $3R$. Accordingly, we present only the results for a circular network of radius $3R$.

The backoff timer in the IEEE 802.11 MAC protocol is drawn from a uniform distribution whose upper bound varies according to the estimated contention level, i.e., a modified binary exponential backoff. Thus, p' takes on dynamic values rather than what we have assumed in the analytical model. Accordingly, we expect that the IEEE 802.11 MAC protocol will operate in a region, while our analysis gives only average performance. In addition, even in network topologies that satisfy the same uniform distribution, we can still get quite different results, which will be shown later.

As we have stated, the IEEE 802.11 MAC protocol cannot ensure collision-free transmission of data packets, even under the assumption of perfect carrier sensing and collision avoidance. There are two reasons for this. One is that the length of a CTS is shorter than that of an RTS, which has been shown to prevent some hidden nodes from backing off [17]. The other reason is that, when a node senses carrier in its surroundings, it does not defer access to the channel for a definite time (which is implicit in other protocols [17]) after the channel is clear. When the interfering node perceives the channel idle and a packet from the upper layer happens to arrive in its buffer, it may transmit immediately after the channel is idle for a DIFS (Distributed InterFrame Space) time, while in fact a data packet transmission may still be going on between another two nodes and collision will occur! This can be illustrated by the simple example shown in Figure 7.

In our simulation, each node has a constant-bit-rate (CBR) traffic generator with data packet size of 1460 bytes, and one of its neighbors is randomly chosen as the destination for each packet generated. All nodes are always backloged. Considering the physical layer's synchronization time as well as propagation delay used in the simulation, the effective packet transmission times are shown in Table 1. For comparison purposes, we map these simulational parameters to equivalent parameters in our analytical model and they are shown in Table 2.

We run both analytical and simulation programs with N = 3, 5 and 8. Though we have not tried to characterize how the performance of the IEEE 802.11 MAC protocol is distributed in the region of values taken by p', we do have generated 50 random topologies that satisfy the uniform distribution and then get an average transmission probability and throughput for the N nodes in the innermost circle of radius R for each configuration. The results are shown in Figure 8, in which the centers of rectangles are the mean values of p' and throughput and their half widths and half heights are the variance of p' and throughput, respectively. These rectangles roughly describe the operating regions of IEEE 802.11 MAC protocol with the configurations we are using.

Figure 8 clearly shows that, IEEE 802.11 cannot achieve the performance predicted in the analysis of correct collision avoidance, but may well outperform the analysis with the same p' for some configurations, especially when N is small. On first thought, it may seem contrary to intuition, given that IEEE 802.11 cannot ensure collision-free data packet transmissions and should always perform worse than analysis results. In fact, the exceedingly high throughput is largely due to the unfairness of the binary exponential backoff (BEB) used in IEEE 802.11. In BEB, a node that just succeeds in sending a data packet resets its contention window to the minimum value, through which it may gain access to the channel again much earlier than other surrounding nodes. Thus, a node may monopolize the channel for a very long time during which there is no contention loss and throughput can be very high for a particular node, while other nodes suffer starvation. We also find that when N increases, the variance of p' and throughput becomes smaller. Thus, the fairness problem is less severe when there are more nodes competing in a shared channel.

Due to the inherent deficiency of the BEB scheme used in the IEEE 802.11 MAC protocol, we investigate a simple variant of this protocol in which the contention window (*CW*) is fixed and then the backoff timer is generated from a uniform distribution with values ranging between 0 and *CW*. We vary the *CW* to get different values of p' and throughput. Though this modified protocol is not fine tuned to the actual number of neighbors that a node may have and thus is not able to deliver the best performance, it is still a much fairer scheme that reflects more realistically how well a contention-based MAC protocol may perform. In order to have a fair comparison of this scheme with the original IEEE 802.11, we reuse the aforementioned network configurations. The *CW* used in our simulations are tabulated in Table 3. The simulation results are shown in Figure 9. For clarity, Figure 9 shows only the operating regions (shown in rectangles) of the modified IEEE 802.11 protocol, without showing details of how each set of the 50 configurations performs. In addition, the median values of p' and throughput are drawn in Figure 9 to show how

the throughput is affected by p' or *CW*, where a larger *CW* means a smaller p'.

Comparing Figures 8 and 9, it is very clear that the modified IEEE 802.11 protocol with a fixed *CW* has a smaller variance of throughput than that in the original protocol and thus is much fairer. To demonstrate this point quantitatively, we obtain both the maximum and the minimum throughput among the innermost N nodes and then calculate the ratio between the maximum and the minimum as an index for fairness. The smaller the ratio is, the fairer is the protocol and vice versa. The results are shown in Table 4. In addition, we can see the degraded performance in the fixed *CW* scheme due to more contention, especially when N is small.

Given that these two protocols cannot ensure that data packets are transmitted free of collisions, the throughput can deviate substantially from what is predicted in the analysis. To demonstrate this, we also collect statistics about the number of transmitted RTS packets that will lead to ACK timeout due to collision of data packets as well as the total number of transmitted RTS packets that can lead to either an incomplete RTS-CTS-data handshake or a successful four-way handshake. Then we calculate the ratio of these two numbers and tabulate the results in Table 5. Table 5 clearly shows that much of the precious channel resource is wasted in sending data packets that cannot be successfully delivered. In addition, in order to decrease the percentage of channel resource wasted due to collisions, a larger contention window should be chosen to artificially decrease the transmission probability of nodes which at the same time lead to longer time wasted in waiting. This is a very typical behavior of collision-avoidance protocols, especially those protocols that do not have a correct collision avoidance scheme. The possibility of collisions of data packets with other packets places a limit on the maximum achievable throughput, which can be significantly lower than the theoretical results that assume a perfect collision avoidance.

Figures 8 and 9 show that the gap in maximum throughput between analytical and simulation results decreases when N increases. This can be explained as follows. When the number of direct competing nodes N increases, the number of indirect competing nodes (hidden terminals, $3N$ on average) also increases, which makes nodes implementing a perfect collision avoidance protocol spend much more time in deferring and backing off to co-ordinate with both direct and indirect competing nodes to avoid collisions. Therefore, much of the gain of perfect collision avoidance is lost and possible spatial reuse is also reduced in a congested area, which makes a perfect collision avoidance protocol work only marginally better than an imperfect one. This observation could not be predicted from previous analytical models or simulations focusing on fully-connected networks or networks with only a limited number of hidden terminals [9–11].

The percentage shown in Table 5 is in fact the β in our extended analysis to explain the deviatory behavior of MAC protocols that do not have perfect collision avoidance. Using these values, we compare the performance of the IEEE 802.11 protocol with that of the adjusted analysis obtained from Equation (6), and show the results in Figure 10. In Figure 10, we only show the results for small values of N as it is not quite meaningful to do the adjustment for large values of N due the reason stated above. Figure 10 shows that the extended analysis is a rather good approximation of the actual performance of the IEEE 802.11 protocol though the latter has larger variation in throughput (possibly due to its inherent fairness problems).

5 Conclusion and Future Work

In this paper, we have used a simple model to derive the saturation throughput of MAC protocols based on an RTS-CTS-data-ACK handshake in multi-hop networks. The results show that these protocols outperform CSMA protocols, even when the overhead of RTS/CTS exchange is rather high, thus showing the importance of correct collision avoidance in random access protocols. More importantly, it is shown that the overall performance of the sender-initiated collision avoidance scheme degrades rather rapidly when the number of competing nodes allowed within a region increases, in contrast to the case of fully-connected networks and networks with limited hidden terminals reported in the literature [9–11], where throughput remains almost the same for a large number of nodes. The significance of the analysis is that the scalability problem of contention-based collision-avoidance MAC protocols looms much earlier than people might expect. Simulation experiments with the IEEE 802.11 MAC protocol and one of its variants validate these observations and show that the IEEE 802.11 MAC protocol can suffer severe degradation in throughput due to its inability to avoid collisions between data packets and other packets even when the number of competing nodes in a region is small. However, when the number of competing nodes in a region increases, the performance gap is smaller as perfect collision avoidance protocols also begins to suffer from exceedingly long waiting time.

Based on both analytical and simulation results, we observe that there are some possible ways to improve the throughput of a sender-initiated collision-avoidance protocol in ad hoc networks. First of all, the simulation results

show that it is very important to ensure correct collision avoidance when the network is less crowded. Using the longer CTS packets proposed in [15], the IEEE 802.11 MAC protocol can lead to much better performance in throughput.

Another obvious way to improve the performance of the IEEE 802.11 protocol is to reduce τ, which includes carrier sensing delay, transmit to receive turnaround time, etc., so as to enlarge the ratio of data packet transmission time to τ. In effect, this implies reducing the transmission power of the nodes and reducing the length of control overhead. Given that RTS and CTS packets cannot be reduced in length and arguably the CTS needs to be lengthened to be sent as a busy tone, the latter requires using piggyback acknowledgments or making acknowledgments optional. An alternative is to combine the sender-initiated handshake with receiver-initiated handshake, as the latter is shown to have less control overhead [2]. However, receive-initiated schemes generally require a good traffic estimator and an adaptive polling discipline at polling nodes to work well, which have not been investigated thoroughly so far.

Because the optimum value of p', i.e., the probability that a node transmits in a time slot, changes with the number of competing nodes within a region, it is necessary to have an adaptive algorithm to achieve optimum performance when the number of active nodes within a region changes. For example, Cali et al. [11] have proposed a way to dynamically tune the IEEE 802.11 protocol to achieve better performance, though it is investigated in static networks. Given that the original BEB scheme has inherent fairness problem and the fixed contention window does not adapt well, it is fair to say that there is still much work left to be done on this topic.

Further work is needed to address the benefits derived from using directional antennas, which entails both directional transmission and directional reception. The rationale behind this is to reduce the actual number of competing nodes within a region thus perfect collision avoidance protocol is more effective and higher maximum throughput may be achieved. The benefits of using directional transmissions have been addressed before [18–20] via simulation experiments, and they are the subject of further analytical work.

References

[1] F. A. Tobagi and L. Kleinrock, “Packet Switching in Radio Channels: Part II - the Hidden Terminal Problem in Carrier Sense Multiple-access Modes and the Busy-tone Solution,” *IEEE Trans. on Communications*, vol. 23, no. 12, pp. 1417–1433, 1975.

[2] J. J. Garcia-Luna-Aceves and A. Tzamaloukas, “Receiver-initiated Collision Avoidance in Wireless Networks,” *ACM Wireless Networks*, vol. 8, pp. 249–263, 2002.

[3] IEEE Computer Society LAN MAN Standards Committee, ed., *IEEE Standard for Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*. IEEE Std 802.11-1997, The Institute of Electrical and Electronics Engineers, New York, 1997.

[4] H. S. Chhaya and S. Gupta, “Throughput and Fairness Properties of Asynchronous Data Transfer Methods in the IEEE 802.11 MAC Protocol,” in *Proc. of PIMRC ’95*, 1995.

[5] S. Chhaya and S. Gupta, “Performance of Asynchronous Data Transfer Methods of IEEE 802.11 MAC Protocol,” *IEEE Pers. Comm.*, vol. 3, Oct. 1996.

[6] G. Bianchi, L. Fratta, and M. Oliveri, “Performance Evaluation and Enhancement of the CSMA/CA MAC Protocol for 802.11 Wireless LANs,” in *Proc. of PIMRC ’96*, pp. 392–396, 1996.

[7] I. Widjaja, B. P. Crow, L. G. Kim, and P. T. Sakai, “Investigation of the IEEE 802.11 Medium Access Control (MAC) Sublayer Functions,” *Proc. of IEEE INFOCOM ’97*, vol. 1, pp. 126–133, 1997.

[8] J. Weinmiller, M. Schläger, A. Festag, and A. Wolisz, “Performance Study of Access Control in Wireless LANs – IEEE 802.11 DFWMAC and ETSI RES 10 Hiperlan,” *ACM/Baltzer Mobile Networks and Applications*, vol. 2, no. 1, pp. 55–67, 1997.

[9] G. Bianchi, “Performance Analysis of the IEEE 802.11 Distributed Coordination Function,” *IEEE Journal on Selected Areas in Communications*, vol. 18, pp. 535–547, Mar. 2000.

[10] F. Cali, M. Conti, and E. Gregori, “IEEE 802.11 Protocol: Design and Performance Evaluation of an Adaptive Backoff Mechanism,” *IEEE Journal on Selected Areas in Communications*, vol. 18, pp. 1774–1786, Sept. 2000.

[11] F. Cali, M. Conti, and E. Gregori, “Dynamic Tuning of the IEEE 802.11 Protocol to Achieve a Theoretical Throughput Limit,” *IEEE/ACM Transactions on Networking*, vol. 8, pp. 785–799, Dec. 2000.

[12] P. Gupta and P. R. Kumar, “The Capacity of Wireless Networks,” *IEEE Trans. on Info. Theory*, vol. 46, pp. 388–404, Mar. 2000.

[13] H. Takagi and L. Kleinrock, “Optimal Transmission Range for Randomly Distributed Packet Radio Terminals,” *IEEE Transactions on Communications*, vol. 32, no. 3, pp. 246–57, 1984.

[14] L. Wu and P. Varshney, “Performance Analysis of CSMA and BTMA Protocols in Multihop Networks (I). Single Channel Case,” *Information Sciences, Elsevier Sciences Inc.*, vol. 120, pp. 159–77, 1999.

[15] J. J. Garcia-Luna-Aceves and C. L. Fullmer, “Floor Acquisition Multiple Access (FAMA) in Single-channel Wireless Networks,” *ACM/Baltzer Mobile Networks and Applications*, vol. 4, no. 3, pp. 157–174, 1999.

[16] X. Zeng, R. Bagrodia, and M. Gerla, “GloMoSim: a Library for Parallel Simulation of Large-scale Wireless Networks,” in *Proc. of the 12th Workshop on Parallel and Distributed Simulations*, May 1998.

[17] C. L. Fullmer and J. J. Garcia-Luna-Aceves, “Solutions to Hidden Terminal Problems in Wireless Networks,” in *Proc. of ACM SIGCOMM ’97*, 1997.

[18] Y.-B. Ko, V. Shankarkumar, and N. H. Vaidya, “Medium Access Control Protocols Using Directional Antennas in Ad Hoc Networks,” in *IEEE INFOCOM 2000*, Mar. 2000.

[19] A. Nasipuri, S. Ye, J. You, and R. E. Hiromoto, “A MAC Protocol for Mobile Ad Hoc Networks Using Directional Antennas,” in *Proc. of the IEEE Wireless Comm. and Networking Conf. (WCNC) 2000*, (Chicago, IL, USA), Sept. 2000.

[20] R. Ramanathan, “On the Performance of Ad Hoc Networks with Beamforming Antennas,” in *ACM MobiHoc ’01*, (Long Beach, CA, U.S.A.), Oct. 2001.

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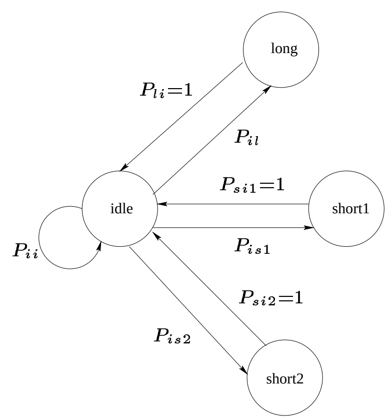


Figure 1: Markov chain model for the channel around a node

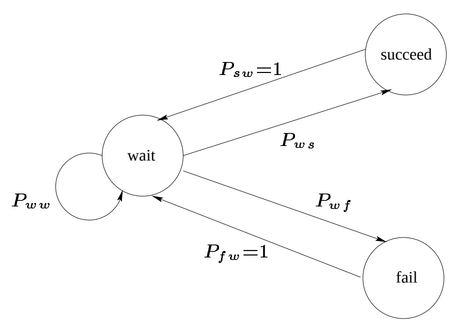


Figure 2: Markov chain model for a node

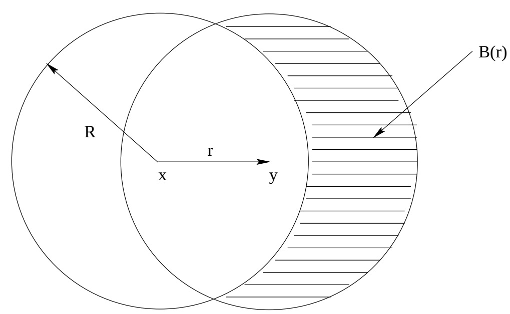
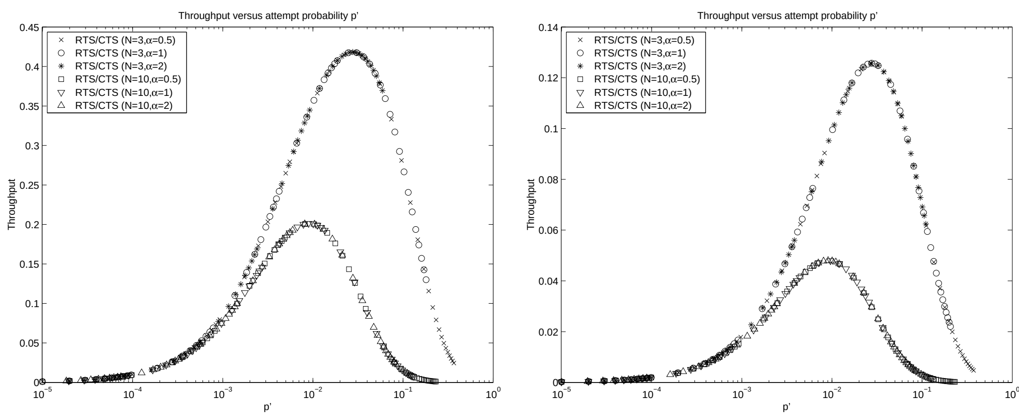


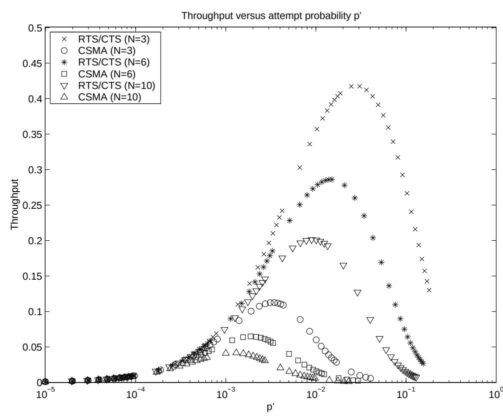
Figure 3: Illustration of “hidden” area



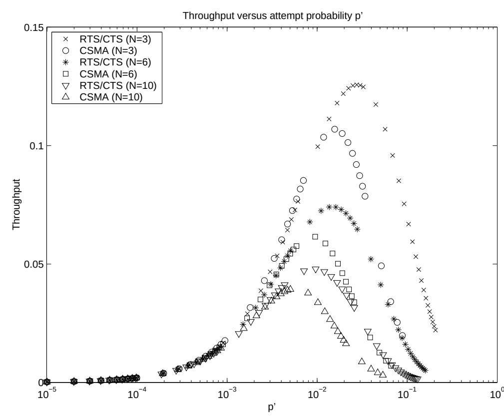
(a) long data packet: $l_{data} = 100\tau$

(b) short data packet: $l_{data} = 20\tau$

Figure 4: α's influence ($l_{rts} = l_{cts} = l_{ack} = 5\tau$)



(a) long data packet: $l_{data} = 100\tau$



(b) short data packet: $l_{data} = 20\tau$

Figure 5: Throughput comparison ($l_{rts} = l_{cts} = l_{ack} = 5\tau$)

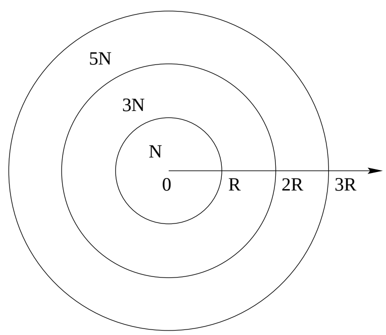


Figure 6: Network Model Illustration

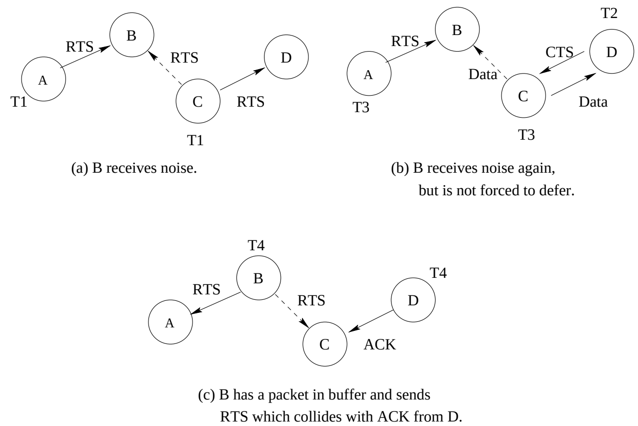
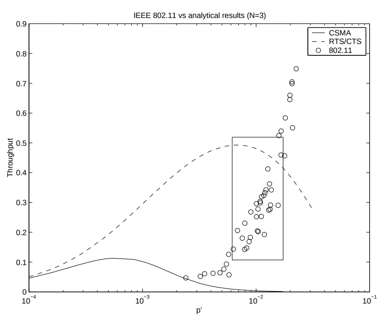
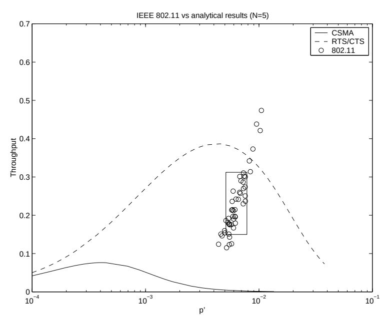


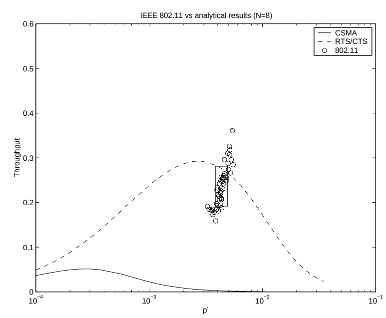
Figure 7: Example of collisions with data packets in the IEEE 802.11 MAC Protocol



(a) $N = 3$

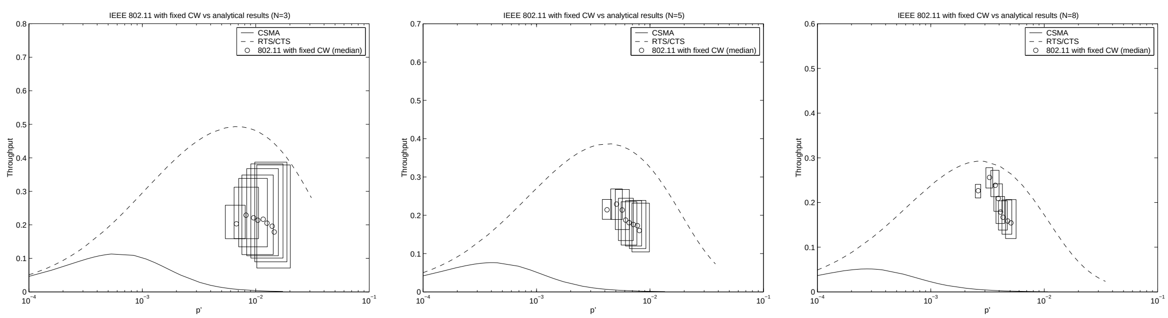


(b) $N = 5$



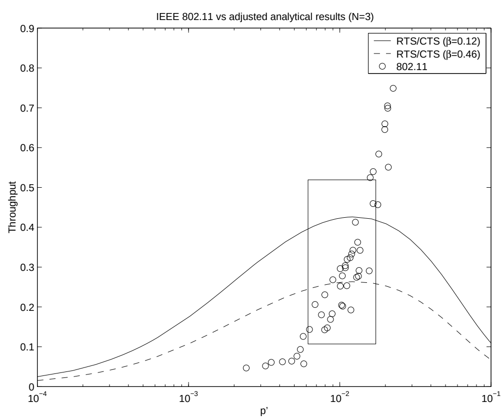
(c) $N = 8$

Figure 8: Performance comparison of IEEE 802.11 with analytical results

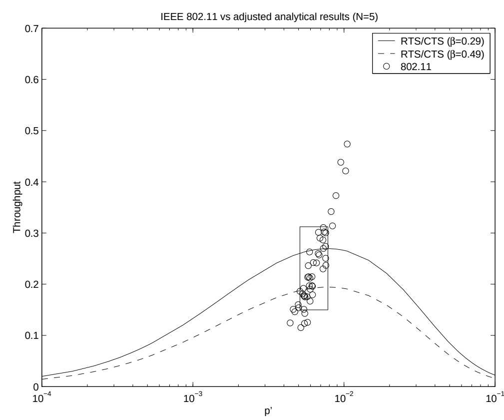


(a) $N = 3$ (b) $N = 5$ (c) $N = 8$

Figure 9: Performance comparison of IEEE 802.11 (fixed CW) with analytical results



(a) $N = 3$



(b) $N = 5$

Figure 10: Performance comparison of IEEE 802.11 with adjusted analytical results

RTS	CTS	data	ACK	DIFS	SIFS
20-byte	14-byte	1460-byte	14-byte	50μsec	10μsec

contention window	slot time	sync. time	prop. delay
31–1023	20μsec	192μsec	1μsec

Table 1: IEEE 802.11 protocol configuration parameters

	τ	l_{rts}	l_{cts}, l_{ack}	l_{data}
actual time	prop. delay + slot time = 21μsec	RTS + sync. time = 272μsec	CTS(ACK) + sync. time = 248μsec	data + sync. time = 6032μsec
normalized	1	13	12	287

Table 2: Equivalent configuration parameters for analytical model

	CW1	CW2	CW3	CW4	CW5	CW6	CW7	CW8
N=3	20	40	80	160	320	640	1280	2560
N=5	30	60	120	240	480	960	1920	3840
N=8	50	100	200	400	800	1600	3200	6400

Table 3: Contention window (CW) used in simulations

	original	CW1	CW2	CW3	CW4	CW5	CW6	CW7	CW8
N=3, mean	10.51	3.77	3.25	3.00	2.99	3.34	2.28	1.81	1.46
N=3, std	15.67	5.30	3.02	2.52	2.90	4.65	1.35	0.75	0.39
N=5, mean	4.54	3.42	2.89	2.65	2.46	2.29	2.04	1.73	1.46
N=5, std	2.99	1.83	1.21	0.89	0.80	0.60	0.53	0.36	0.22
N=8, mean	3.45	3.57	2.88	2.75	2.39	2.16	1.95	1.69	1.46
N=8, std	1.59	3.11	1.47	1.70	0.87	0.73	0.58	0.35	0.39

Table 4: Fairness comparison of BEB scheme and fixed *CW*

	original	CW1	CW2	CW3	CW4	CW5	CW6	CW7	CW8
N=3, mean	0.29	0.49	0.46	0.43	0.41	0.39	0.33	0.23	0.14
N=3, std	0.17	0.20	0.18	0.17	0.17	0.17	0.15	0.11	0.07
N=5, mean	0.39	0.56	0.54	0.53	0.51	0.47	0.37	0.25	0.15
N=5, std	0.10	0.10	0.10	0.10	0.10	0.10	0.09	0.07	0.04
N=8, mean	0.44	0.59	0.58	0.56	0.53	0.44	0.33	0.21	0.14
N=8, std	0.06	0.07	0.07	0.06	0.06	0.06	0.05	0.04	0.07

Table 5: Percentage of ACK timeout in BEB scheme and fixed *CW*